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ADVISORY CIRCULAR

USE OF NONDESTRUCTIVE TESTING DEVICES IN THE EVALUATION OF AIRPORT PAVEMENTS

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

Initiated by: AAS-200

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FEDERAL AVIATION ADMINISTRATION

SUBJECT: USE OF NONDESTRUCTIVE TESTING DEVICES IN THE EVALUATION OF AIRPORT PAVEMENTS

1. PURPOSE. This advisory circular provides guidance to the public on the use of nondestructive testing devices as aids in the evaluation of the load-carrying capacity of airport pavements.

2. RELATED READING MATERIAL. The publications listed in appendix 2 provide further information on the evaluation of airport pavements.

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CHAPTER 1. USE OF NONDESTRUCTIVE TESTING DEVICES ON AIRPORT PAVEMENTS

1. GENERAL. This chapter provides technical guidance on the use of nondestructive testing devices as aids in the evaluation of airport pavements. The guidance is rather general as each situation must be considered separately, based on local conditions.

2. BACKGROUND. Nondestructive testing of airport pavements for the purpose of establishing load-carrying capacity is highly desirable due to the potential for substantial savings in time and costs over destructive testing methods. The Federal Aviation Administration (FAA) is currently funding a sizeable research effort intended to provide specifications for a nondestructive pavement testing device and methodology for determining the load-carrying capacity of airport pavements. The research effort has provided preliminary information which is considered applicable to all nondestructive test equipment. Although research effort was primarily developed from studies involving air carrier-type pavements, the procedures and principles are also applicable to general aviation facilities. Guidance in this chapter applies to qualitative nondestructive testing; i.e., tests intended to provide a relative measure between test points. In these instances a followup destructive testing program should be performed in order to evaluate the actual load-carrying capacity of airport pavements. This information is applicable to any commercially available equipment provided the applied loads are sufficiently large to provide reliable results. Information concerning the eligibility of nondestructive testing for Federal funding should be obtained from FAA Airports field offices.

3. TEST PLAN. It is recommended that the office responsible for approval require a detailed test plan. It should describe the equipment to be used, the number and location of test sites, the method of analyzing the test results, and the followup program of destructive testing. It should state how the nondestructive test results will be used in conjunction with the destructive test program.

4. EQUIPMENT AND TEST PROCEDURES.

   a. General. Conceptually, the adequacy of the test plan should be judged by its ability to provide sufficient information suitable for the pavement, foundation, and aircraft conditions under study. The considerations set forth in this paragraph are intended to provide detailed assistance in determining the technical adequacy of the nondestructive test plan.

b. Test Equipment. Vibratory loading devices intended to perform nondestructive tests on pavements operate using essentially the same general principle. A dynamic load is generated which alternately adds and subtracts from the static weight of the test apparatus, usually in a sinusoidal wave form. The static weight of the vibratory device must be larger than the alternating dynamic force to insure that the device will remain in contact with the pavement while it is in operation. The load is applied to the pavement through loading plates or wheels. The deflection response of the pavement is sensed by either velocity or accelerometer transducers and is electronically converted to produce a measurement of deflection. Velocity measurements are integrated once to produce deflection values, and acceleration readings are double integrated to obtain deflection values. An evaluation of the stiffness or strength of the pavement is then made by studying the magnitude of the deflections. In some instances more than one response transducer is used allowing measurements at several points within the deflection basin. The frequency of the dynamic load has an influence on pavement response. Loads applied near the resonant frequency will produce larger deflections than deflections resulting from loads applied at other frequencies. Load and frequency are discussed separately in more detail in the following subparagraphs (1) and (2).

(1) Load. The load deflection relationship of pavements is often nonlinear, and test results obtained by using small loads which have to be extrapolated over one or two orders of magnitude can result in serious errors. Research to date has indicated that nondestructive testing equipment should be capable of producing a dynamic deflection of at least 0.0005 inch (0.013 mm) to provide reliable results. Tables 1-1 and 1-2 of recommended minimum dynamic loads have been developed for rigid and flexible pavements respectively, which should provide for the minimum deflection of 0.0005 inch (0.013 mm). In developing these tables the pavements were assumed to be supported on subgrade moduli of 100 pci (2.8 kg/cm^3), 300 pci (8.3 kg/cm^3), and 500 pci (13.8 kg/cm^3) in the case of rigid pavements. Flexible pavements were assumed to be supported on F1, F5, and F10 subgrade materials. Due to the damping of the foundation, the dynamic load was assumed to produce a deflection equal to 50 percent of the deflection of a static load of equal magnitude.

TABLE 1-1. RECOMMENDED MINIMUM DYNAMIC LOADS FOR NONDESTRUCTIVE TESTING OF RIGID PAVEMENTS

Rigid Pavement Thickness Inches (Millimeters)		Recommended Minimum Dynamic Load Pounds (Newtons)					
		k=100a/		k=300b/		k=500c/	
6	(150)	700	(3,100)	1,200	(5,350)	1,550	(6,900)
8	(200)	1,050	(4,650)	1,850	(8,250)	2,350	(10,450)
10	(250)	1,500	(6,650)	2,550	(11,350)	3,300	(14,700)
12	(300)	1,950	(8,650)	3,350	(14,900)	4,350	(19,350)
14	(360)	2,450	(10,900)	4,250	(18,900)	5,450	(24,250)
16	(410)	3,000	(13,350)	5,200	(23,150)	6,700	(29,800)
18	(460)	3,600	(16,000)	6,200	(27,600)	8,000	(35,600)
20	(510)	4,200	(18,700)	7,250	(32,250)	9,350	(41,600)
22	(560)	4,800	(21,350)	8,350	(37,150)	10,800	(48,050)
24	(610)	5,500	(24,450)	9,500	(42,250)	12,300	(54,700)

a/ k=100 pci = 2.8 kg/cm^3

b/ k=300 pci = 8.3 kg/cm^3

c/ k=500 pci = 13.8 kg/cm^3

TABLE 1-2. RECOMMENDED MINIMUM DYNAMIC LOADS FOR NONDESTRUCTIVE TESTING OF FLEXIBLE PAVEMENTS

Flexible Pavement Thickness Inches (Millimeters)		Recommended Minimum Dynamic Load Pounds (Newtons)					
		F1		F5		F10	
8	(200)	1,500	(6,650)	550	(2,450)	300	(1,350)
12	(300)	1,900	(8,450)	700	(3,100)	400	(1,800)
16	(410)	2,050	(9,100)	850	(3,800)	500	(2,200)
20	(510)	2,300	(10,250)	950	(4,250)	600	(2,650)
24	(610)	2,500	(11,100)	1,000	(4,450)	700	(3,100)
28	(710)	2,550	(11,350)	1,150	(5,100)	750	(3,350)
32	(810)	2,600	(11,550)	1,200	(5,350)	850	(3,800)
36	(910)	2,650	(11,800)	1,400	(6,250)	900	(4,000)

Note: These recommended loadings are to be used only as general guides and do not constitute absolute values. The controlling criterion should be a deflection response of at least 0.0005 inch (0.013 mm). The loadings recommended in tables 1-1 and 1-2 are based on assumed subgrade strengths and damping coefficients which may not be satisfied for a particular situation. Different subgrade strengths and damping coefficients will require a change in the magnitude of the dynamic load to produce 0.0005-inch (0.013 mm) deflection. The minimum deflection criterion was determined from preliminary research results. The reason for establishing a minimum value for deflection is to provide a response of sufficient magnitude to influence a significant portion of the pavement structure and to exceed the nonlinear portion of the load deflection curve.

(2) Frequency. Ideally, the frequency of the vibratory loading should be such that the maximum depth of influence into the pavement structure is achieved. Unfortunately, there is no practical method of determining the depth of penetration on an operational pavement. Nondestructive testing devices should be operated at the frequency specified by the manufacturer. Testing devices with large variable frequency ranges should be operated at the frequency producing maximum deflection, if the manufacturer does not recommend a testing frequency. The maximum deflection will normally occur at a frequency below 25 Hz.

c. Number and Location of Test Sites. One of the inherent advantages of nondestructive testing is the large number of tests which can be performed in a relatively short time. A rule of thumb recommended for determining the number of test sites is that each test site should represent about 15,000 square feet (1,400 square meters) of pavement when the pavement section, subgrade conditions, and construction history are uniform. Variations in section, subgrade conditions, and/or construction history will usually require an increase in the number of test sites.

(1) Rigid Pavements. Generally, nondestructive tests on rigid airport pavements should be located near the center of the slab panels. Tests performed near free edges, jointed edges, corners, or cracks may lead to erroneous results as any warping or curling of the slabs will be pronounced in these locations. Cracks and joints drastically affect the structural rigidity of slabs and have a decided influence on nondestructive test results. Tests in the vicinity of joints and/or cracks may be performed and compared with

center-of-slab tests. However, attempts to calculate joint efficiency must be carefully done. Joint or crack opening widths have the greatest influence on joint efficiency. In addition, efficiency is influenced by warping, curling, and foundation support. Calculation of joint efficiency should recognize that efficiency and load distribution are functions of many variables and are subject to daily changes. Some testing near and across joints using more than one response pickup has been performed in research studies in an attempt to measure joint efficiency. The results of these tests are inconclusive because of the large number of factors which influence joint efficiency, making interpretation of the data nearly impossible in terms of general conclusions which have broad application.

(2) Flexible Pavements. Flexible pavements are not as sensitive to test location as rigid pavements. Nondestructive tests on flexible pavements should not be purposely performed in badly cracked or rutted areas unless these areas are representative of the entire feature. The deflection response of flexible pavements is sensitive to temperature changes. Since nondestructive tests will, in all probability, be performed during periods of changing pavement temperatures, all readings should be corrected to a common base temperature. Temperature corrections are discussed in paragraph 5 of appendix 1.

(3) Inpavement Facilities. It is advisable to avoid performing nondestructive tests near inpavement facilities, such as light fixtures, buried conduit, or drainage facilities, on any type of pavement. This is particularly true of flexible pavements and, to a lesser degree, rigid pavements. If possible, the tests should be located such that no tests are performed within 5 feet (1.5 meters) of inpavement facilities. The reason for recommending avoidance of inpavement facilities is that nondestructive testing technology is not sufficiently advanced to quantify the influence of these facilities on the test data. The possibility of damaging inpavement facilities by operation of a nondestructive testing device is very small.

d. Climate Considerations. Since the nondestructive tests discussed in this chapter will usually be compared with each other on a relative basis, it is recommended that tests not be performed when the pavement structure is frozen or during the spring thaw period. A frozen section will be extremely rigid, and it is likely that very little or possibly no differences in response will be detected. The reverse is true during the spring thaw period in that the pavement will be in a weakened condition in all areas and differences in response will be minimal.

e. Deflection Basins. Through the use of more than one response transducer, it is possible to develop data on the shape of the deflection basin. Often the shape of the deflection basin will be useful in determining relative differences in stiffness between data points.

5. ANALYSIS OF TEST RESULTS.

a. General. Nondestructive testing will provide a large number of readings which should be analyzed using statistical techniques. Much of this chapter contains illustrations of basic statistical concepts which can be applied to nondestructive test data. These statistical procedures are presented in an effort to encourage examination of the raw data to facilitate engineering judgment, rather than just "taking the average." Test results should be reported in standard statistical terms. As a minimum, each particular pavement feature (runway, taxiway, etc.) should be identified and all raw data summarized and tabulated. The mean and standard deviation of all nondestructive tests performed on each pavement feature should be included in the summary. As a general guide, destructive tests should be performed in areas which are representative of the condition of the pavement feature in question. Destructive tests should be performed generally at a location which is one standard deviation removed from the mean in the conservative direction. The conservative direction would be toward higher deflection readings; i.e., mean deflection plus one standard deviation. A higher deflection indicates a weaker pavement structure. By testing at one standard deviation from the mean, the destructive test results will, by definition, be conservative for 84 percent of the data.

(1) Example. To illustrate the above procedure, assume the following nondestructive test data were collected on a pavement feature.

Nondestructive Test Number	Measured Deflection Inches	(mm)
1	0.00054	(0.0137)
2	0.00059	(0.0150)
3	0.00062	(0.0157)
4	0.00056	(0.0142)
5	0.00054	(0.0137)
6	0.00057	(0.0145)

7	0.00055	(0.0140)
8	0.00056	(0.0142)
9	0.00058	(0.0147)
10	0.00055	(0.0140)
Total =	0.00566	(0.1438)

Mean = Total ÷ number of readings = .000566 in. (0.0144 mm)

$$\text{Standard Deviation} = \sqrt{\frac{\Sigma X^2}{N-1} - \frac{(\Sigma X)^2}{N\ (N-1)}}$$

where ΣX^2 = Summation of each reading squared

$(\Sigma X)^2$ = Square of the total of all readings

N = Number of readings

Standard Deviation for above data

$$= \sqrt{\frac{.00000321}{9} - \frac{(0.00566)^2}{10 \times 9}}$$

$= 0.000025$ in. (0.00064 mm)

Mean plus one Standard Deviation = 0.00059 (0.0150 mm)

In this example a destructive test in the vicinity of nondestructive test number 2 or 9 should be considered.

b. Various Data Conditions. Due to the large number of tests which can be performed using nondestructive testing techniques, the data generated may come in a variety of forms, depending on the variability of the pavement strength. Several possible data conditions are discussed in this paragraph. These conditions are by no means intended to cover all possible conditions but are discussed here to illustrate the need to carefully examine the data and use judgment along with statistical analysis.

(1) Highly Variable Data. Data which are highly variable; i.e., those with a large standard deviation, should be examined closely to determine if the high standard deviation is due to overall data scatter or due to only one or two data points. If the high standard deviation is due to overall data scatter, the destructive tests should be performed as recommended in paragraph 5a above. If the large standard deviation is due to one or two data points, a decision must be made as to whether or not these points should be discarded as nonrepresentative. If possible the

areas showing peculiar readings should be retested to determine if an error has been made. The peculiar readings may also be indicators of potential distress areas. The decision to discard or retain data points is, of course, a judgment which is dependent on the individual case and circumstances and no specific guidelines can be given.

(2) Grouped Data. Data may tend to fall into two or more groups on pavement features which are thought to be constant. For example, a section of a parking apron shows lower deflection values than the remainder of the parking apron. In this example the question arises as to whether or not the difference in the groups of data is significant. A standard statistical procedure is available to determine if the difference is significant. The procedure is called the analysis of differences between means. An example of a set of grouped data follows:

(a) Example:

Nondestructive Test Number	Measured Deflection Inches	(mm)
1	0.00084	(0.0213)
2	0.00079	(0.0201)
3	0.00087	(0.0221)
4	0.00081	(0.0206)
5	0.00078	(0.0198)
6	0.00083	(0.0211)
7	0.00057	(0.0145)
8	0.00060	(0.0152)
9	0.00059	(0.0150)
10	0.00060	(0.0152)
11	0.00058	(0.0147)
12	0.00061	(0.0155)

In this data set, tests 1 through 6 are in the vicinity of 0.0008 inch (.0203 mm) and tests 7 through 12 are in the vicinity of 0.0006 inch (.0152 mm). The problem becomes one of determining if the differences are due to normal data scatter or if the two areas are significantly different. The average and standard deviation for tests 1 through 6 are 0.00082 inch (.0206 mm) and 0.000033 inch (.0008 mm), respectively. The average and standard deviation for tests 7 through 12 are 0.00059 inch (.0150 mm) and 0.000015 inch (.0004 mm), respectively. A statistic commonly denoted as t can be computed using the following formula:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{(N_1 - 1)\, S_1^{\,2} + (N_2 - 1)\, S_2^{\,2}} \cdot \sqrt{\frac{1}{N_1} + \frac{1}{N_2}}}$$

where $\bar{X}_1$ = mean of group 1

$\bar{X}_2$ = mean of group 2

N_1 = number of observations in group 1

N_2 = number of observations in group 2

S_1 = standard deviation of group 1

S_2 = standard deviation of group 2

In the example

$$t = \frac{0.00082 - 0.00059}{\sqrt{(6-1)\ (0.000033)^2 + (6-1)\ (0.000015)^2} \cdot \sqrt{\frac{1}{6} + \frac{1}{6}}}$$

$t = 19.2$

The statistic t computed above is used in comparing different data sets. Testing of hypotheses is a standard technique in statistics where the hypothesis is set forward that the mean of one data group is equal to the mean of the other data group. After computing the statistic t, it is compared with "Student's t-distribution" value for the appropriate number of degrees of freedom and percent confidence. Tables of the Student's t-distribution can be found in practically any reference on statistics and probability. The degrees of freedom are defined as the total number of tests minus 2. In the example the degrees of freedom would be 12 - 2 = 10. Using a level of significance of 5 percent (this level can be varied as required; in this example 5 percent was chosen arbitrarily), which means, there is a 5 percent chance for error or conversely we are 95 percent sure of selecting a correct answer. Referring to the table of Student's t-distribution in the Chemical Rubber Company(CRC) Handbook of Tables for Probability and Statistics using 10 degrees of freedom and a 5 percent level of significance, the value of t is 2.228. Since the computed value of t is larger than the tabulated value, the hypothesis that the means are equal is rejected. By rejecting the hypothesis, it is concluded with 95 percent confidence that tests 1 through 6 are truly different from tests 7 through 12 and should be treated separately. In the example, two destructive tests would be recommended; one near Nondestructive Test (NDT) Number 1 and one near NDT Number 12. These tests should provide a reasonable estimate of the pavement strength which is on the conservative side.

Note: An excellent discussion on tests of hypotheses can be found in Modern Elementary Statistics, by John E. Freund, Prentice Hall, Inc., Englewood Cliffs, New Jersey, 1960. Most textbooks on elementary statistics discuss tests of hypotheses which include differences between means. Tables of Student's t-distribution can be found in numerous textbooks and/or handbooks on statistical analysis.

c. Presentation of Data. In addition to tabulating and summarizing data, a better understanding of the condition of the pavement can sometimes be achieved by displaying data in the form of profile and/or contour plots. Profile or contour plots can also be valuable for airport sponsors as a permanent record of testing. These plots also convey a better overall picture than tabulated data.

6. SUMMARY. The information discussed above applies to the use of nondestructive testing to assist in conducting a destructive test program to evaluate the load-carrying capacity of airport pavements. A number of different devices are available to perform these tests. The Benkleman beam, for example, senses the deflection of a pavement under an actual loading configuration. Some electronic devices sense cracked pavements by wave velocity measurements. While these devices can prove useful in some instances, the use of results from devices of this type must be tempered by engineering judgment.

CHAPTER 2. EVALUATION OF LOAD-CARRYING CAPACITY BY NONDESTRUCTIVE MEANS

1. GENERAL. This chapter provides information necessary to calculate load-carrying capacity from nondestructive tests. It should be noted that some destructive testing is required but should be minimal.

2. BACKGROUND.

   a. The Federal Aviation Administration (FAA) is presently funding a rather large research study in nondestructive testing as previously mentioned. In September 1974, an Airport Pavement Bulletin entitled, Nondestructive Testing, No. FAA-74-1, (appendix 1) was published by the FAA Systems Research and Development Service. This bulletin describes the equipment and methodology developed in the research study being conducted by the U. S. Army, Corps of Engineers, Waterways Experiment Station. The methodology developed in this study is applicable to only conventional, rigid, or flexible pavement and to equipment similar to that developed by the Corps of Engineers. The methodology is based on the following assumptions:

      (1) The controlling stress in rigid pavement evaluation is assumed to be the flexural stress in the pavement slab.

      (2) The weakest component of the flexible pavement structure is assumed to be the subgrade. If these assumptions are invalid for a particular situation the methodolgy will yield erroneous results. When "unconventional" pavements are tested, it will be necessary to convert to "conventional" sections and/or develop correlations with the dynamic tests. Definitions of conventional pavements are given in paragraph 2 of appendix 1.

   b. The methodology still requires some conventional analysis (destructive testing and inoffice evaluation); however, it is minimized. Application of this recently developed procedure is encouraged but because the equipment is not readily available, use will probably be somewhat restricted. Arrangements to use the prototype equipment have to be handled through the U. S. Army, Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi. Methodologies other than that presented in appendix 1 are used by some engineers for pavement evaluation. Use of other methodologies should be checked using this appendix and any available destructive test data. Approval to use a methodology other than that presented in the appendix should be handled on a case-by-case basis.

3. EVALUATION METHOD. The description of the test equipment and the evaluation methodology are presented in the Airport Pavement Bulletin, No. FAA-74-1, which is included as appendix 1.

NOTE: Bulletin No. FAA-74-1 was superseded by SRDS Report No. FAA-RD-73-205-I, Nondestructive Vibratory Testing of Airport Pavements, dated September 1975. The bulletin represents a condensation of the report and for practical applications yields substantially the same results. The bulletin has been included rather than the report for the sake of brevity and user convenience.

No. FAA-74-1

BULLETIN
Airport Pavement

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NONDESTRUCTIVE TESTING

September 1974

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

This Airport Pavement Bulletin is released for users information only. It has been recognized that results of engineering projects are often. delayed for considerable periods of time (sometimes 6 to 18 months) pending the preparation, review, rewrite and issuance of the final technical report. In order that the major findings of these efforts may be available to users without delay, this bulletin has been prepared for advance information only. Upon release of SRDS Report No. FAA-RD 73-205-I, Nondestructive Vibratory Testing of Airport Pavement, expected early in 1975, this bulletin is cancelled and should be discarded. Similar bulletins on other pavement subjects will be released when the data is available.

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BULLETIN FOR NONDESTRUCTIVE TESTING EVALUATION OF AIRPORT PAVEMENTS

1 INTRODUCTION

This report describes a procedure for the determination of the load-carrying capacity of airport pavement systems using nondestructive testing (NDT) techniques. The equipment and procedures have been developed by the Corps of Engineers in response to a need of the Federal Aviation Administration (FAA) and Army for making rapid evaluations of pavement systems with a minimum of interference to normal airport operations.

Little research was conducted in the field of NDT until about the mid-1950's when Royal Dutch Shell Laboratory researchers began a study of vibratory loading devices to evaluate flexible pavements. Many other agencies have since investigated the use of NDT techniques to evaluate pavements. The U. S. Army Engineer Waterways Experiment Station (WES) conducted minimal research using various types of vibratory equipment during the 1950's and 1960's. Much of the early WES work emphasized attempts to measure the elastic properties of the various layers of pavement materials using wave propagation measurements. The basic approach involved use of these elastic constants along with multilayered theory for computation of allowable aircraft loadings. In 1970, an improved vibratory loading device was developed by the Army, and, in 1972, WES began a study for the FAA to develop an NDT evaluation procedure. To meet the FAA time frame, the primary effort has been directed toward developing a procedure based upon measuring the dynamic stiffness modulus (DSM) of the pavement system and relating this value to pavement performance data. Work is continuing on the development of a methodology for measuring the elastic constants of the various layers using NDT techniques; however, this method has not yet been developed to an acceptable level of confidence.

2 APPLICATIONS

The NDT evaluation procedure reported herein is applicable only to conventional rigid and flexible pavement systems. A conventional rigid pavement consists of a nonreinforced concrete surfacing layer on nonstabilized base and/or subgrade materials. A conventional flexible pavement consists of a thin (6-in. or less) bituminous surfacing layer on nonstabilized layers of base, subbase, and subgrade materials. Work is currently underway to extend the NDT procedure to other types of pavement systems which incorporate such other variables as thick bituminous surfacings and stabilized layers.

3 EQUIPMENT

The evaluation procedure contained herein requires the determination of the response of the pavement system to a specific steady state vibratory loading. Inasmuch as the response of materials making up the pavement system to loading is generally nonlinear, the determination of the pavement response for use in the evaluation procedure contained herein requires a specific loading system. The loading device must exert a static load of 16 kips on the pavement and be capable of producing 0- to 15-kip peak vibratory loads at a frequency of 15 Hz. The load is applied to the pavement surface through an 18-in.-diam steel load plate. The vibratory load is monitored by means of three load cells mounted between the actuator and the load plate, and the pavement response is measured by means of velocity transducers mounted on the load plate. Automatic data recording and processing equipment is a necessity. The loading device must be readily transportable to accomplish a large number of tests in a minimum amount of time, thus avoiding interference with normal airport operations. The WES NDT equipment is mounted in a tractor-trailer unit as shown in Figure 1.

4 DATA COLLECTION

In the evaluation procedure, the response of the pavement system to vibratory loading is expressed in terms of the DSM. Since the time required to measure a DSM at each testing point is short (2 to 4 min), a large number of DSM measurements can be made during the normal evaluation period. On runways and primary and high-speed taxiways, DSM tests should be made at least every 250 ft on alternate sides of the facility center line along the main gear wheel paths. For secondary taxiway systems or lesser used runways, DSM tests should be made about every 500 ft on alternate sides of the center line. For apron areas, DSM tests should be conducted in a grid pattern with spacings between 250 and 500 ft. Additional tests should be made where wide variations in DSM values are found, depending upon the desired

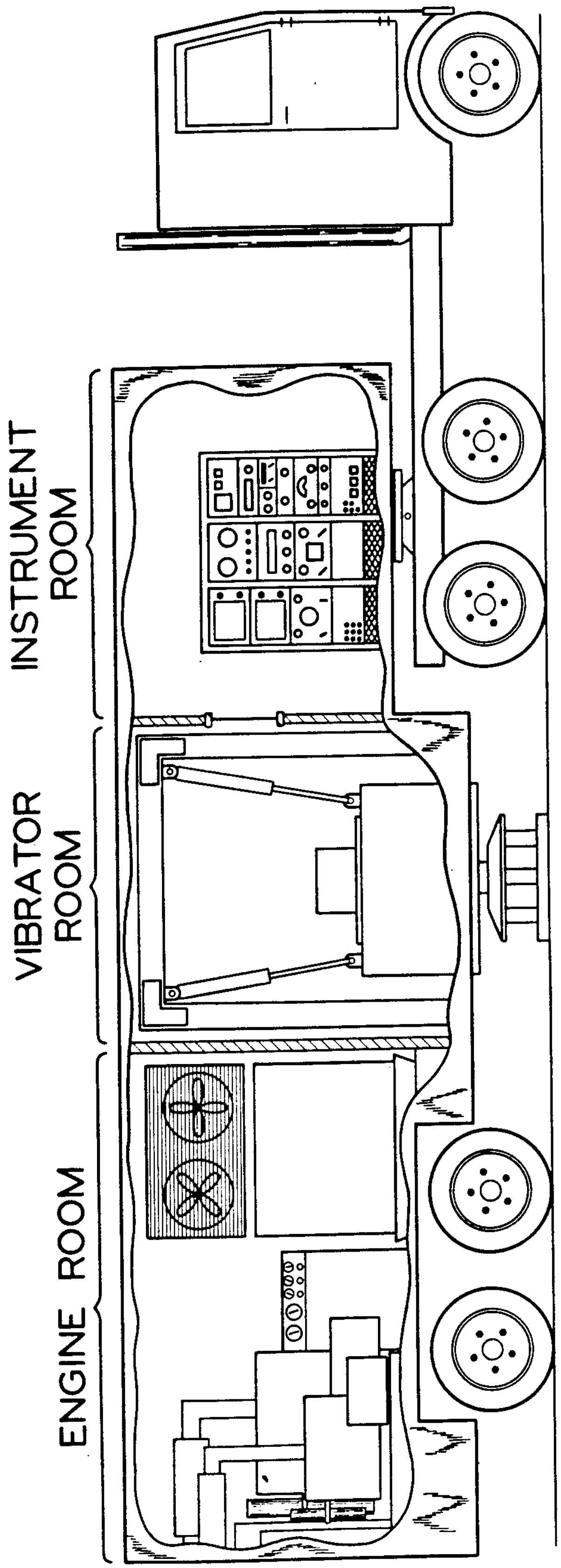

Figure 1. WES NDT equipment

thoroughness of the evaluation. DSM measurements for rigid pavements must be made in the interior (near the center) of the slab. The layout of DSM test sites and selection of DSM values for evaluation must consider the various pavement types, pavement sections, and construction dates. Thus, a thorough study of as-built pavement drawings is particularly helpful in designing the testing program. After the DSM tests have been performed and grouped according to pavement type and construction, a representative DSM value should be selected (as described below) for computation of the allowable loading.

At each test site, the loading equipment is positioned, and the dynamic force is varied from 0 to 15 kips at 2-kip intervals at a constant frequency of 15 Hz. The deflection of the pavement surface, measured by the velocity transducers, is plotted versus the applied load as shown in Figure 2. The DSM (corrected as described below) is the inverse of the slope of the deflection versus load plot (see Figure 2).

In addition to the DSM measurement, it is necessary to know the pavement type (rigid or flexible) and the thicknesses and material classifications of each layer making up the pavement section. These parameters can be determined from the construction (as-built) drawings or by drilling small-diameter holes through the pavement.

When the evaluation is for flexible pavement, the temperature of the bituminous material must be determined at the time of test. This can be determined by directly measuring the temperatures with thermometers installed 1 in. below the top, 1 in. above the bottom, and at the middepth of the bituminous layer and averaging the values to obtain the mean pavement temperature or by measuring the pavement surface and air temperatures and using Figure 3 to estimate the mean pavement temperature.

5 DATA CORRECTION

The load-deflection response of many pavements, particularly flexible pavements, is nonlinear at the lower force levels but becomes more linear at the higher force levels (12 to 15 kips). In such cases, a correction is applied to the load-deflection curve so that the DSM is obtained from the linear portion of the curve (see Figure 2).

The modulus of bituminous materials is highly dependent upon temperature, so an adjustment in the measured DSM must be made if the temperature of the bituminous material at the time of test is other than 70 F. The correction is made by entering Figure 4 with the measured or calculated mean pavement temperature and determining the DSM temperature adjustment factor by which the measured DSM should be multiplied.

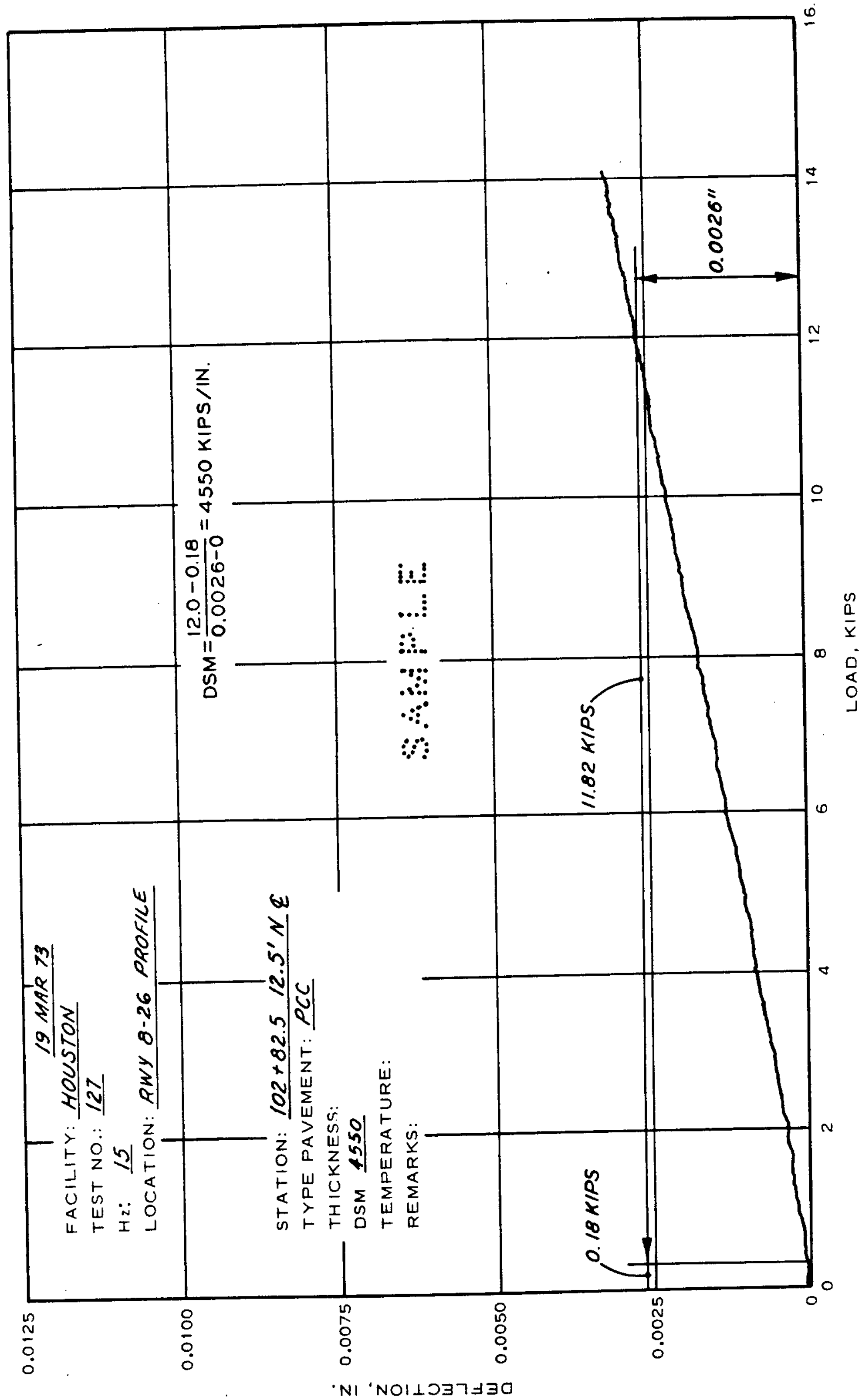

Figure 2. Deflection versus load (sample plot)

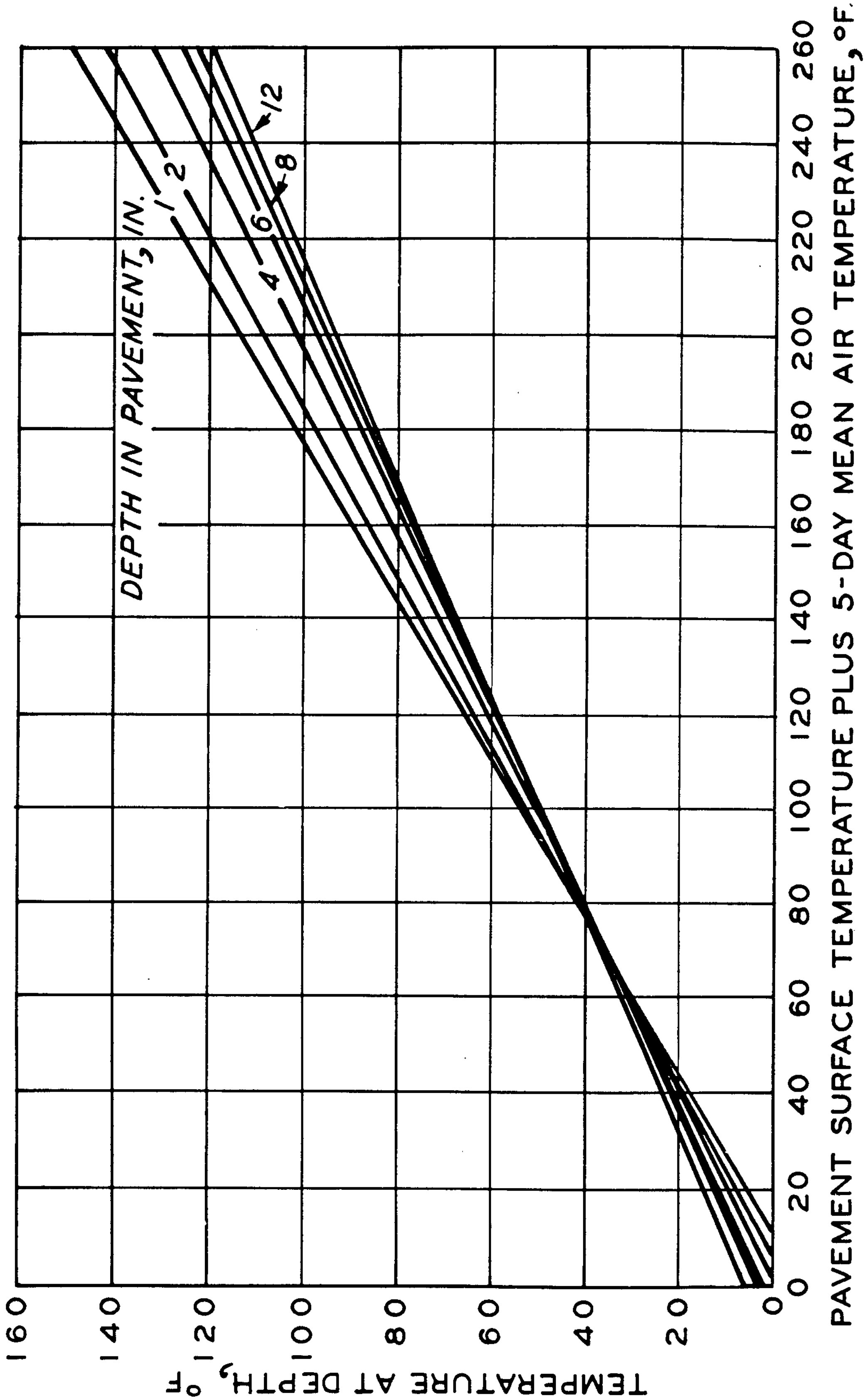

Figure 3. Prediction of flexible pavement temperatures

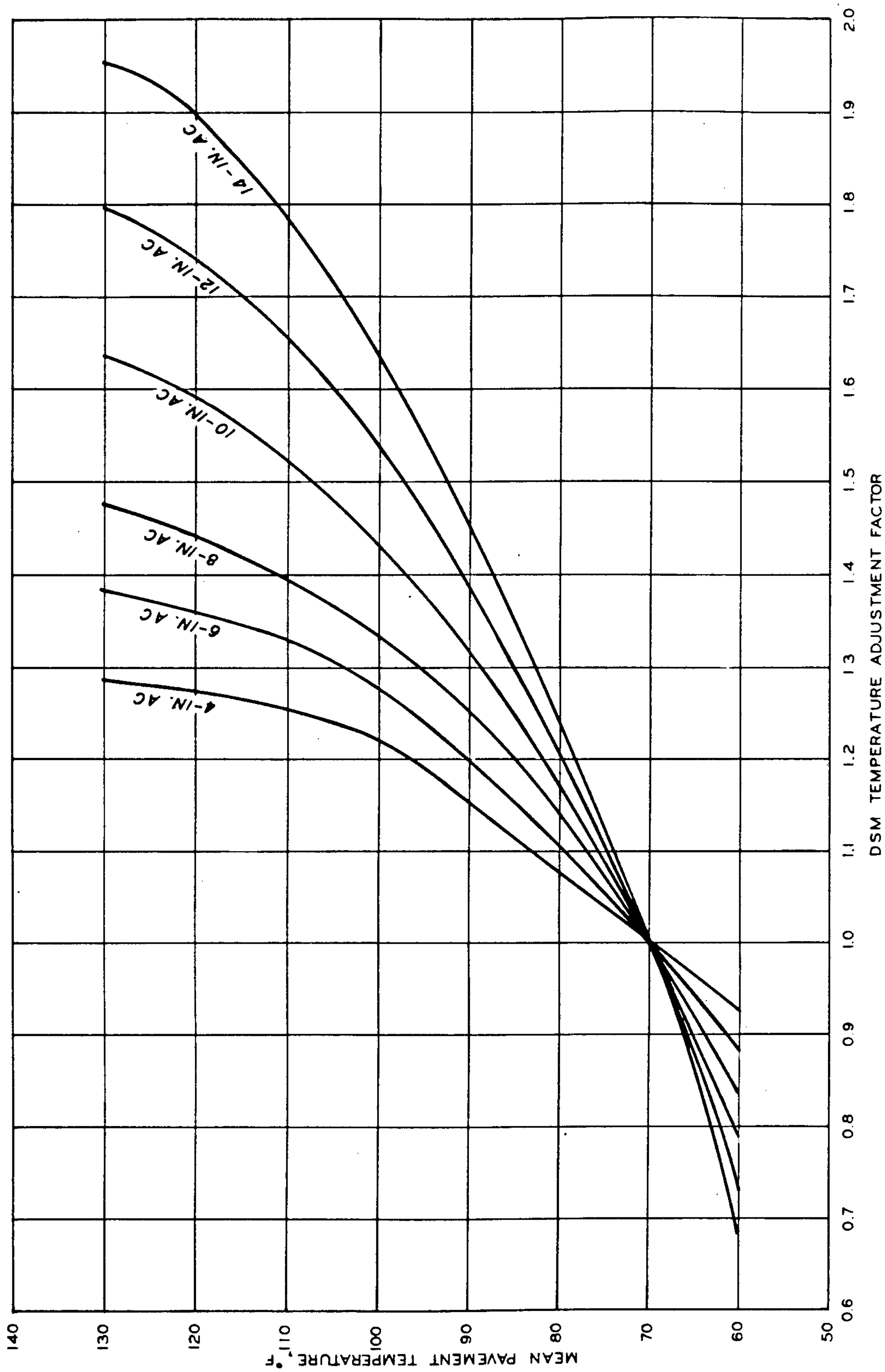

Figure 4. DSM temperature adjustment curves

The DSM and load-carrying capacity of a pavement system can be significantly changed by the freezing and thawing of the materials, especially when frost penetrates a frost-susceptible layer of material. Correction factors to account for these conditions have not been developed. Therefore, the evaluation should be based on the normal temperature range, and, if a frost evaluation is desired, the DSM should be determined during the frost melting period.

A representative DSM value must be selected for each pavement group to be evaluated. Although a section of pavement may supposedly be of the same type and construction, it should be treated as more than one pavement group when the DSM values measured in one section of the pavement are greatly different from those in another section. The DSM value to be assigned to a pavement group for evaluation purposes will be determined by subtracting one standard deviation from the statistical mean.

6 DETERMINATION OF ALLOWABLE AIRCRAFT LOAD

After determination and correction of the measurement of the DSM, the evaluation procedure depends upon the type of pavement, rigid or flexible.

6.1 Rigid Pavement Evaluation

6.1.1 Step 1

The corrected DSM is used to enter Figure 5 and determine the allowable single-wheel load.

6.1.2 Step 2

The radius of relative stiffness ℓ is computed as

$$\ell = 24.2\sqrt[4]{\frac{h^3}{F_F}}$$

where

h = thickness of the concrete slab, in.

F_F = foundation strength factor determined from Figure 6 using the FAA subgrade soil group classification

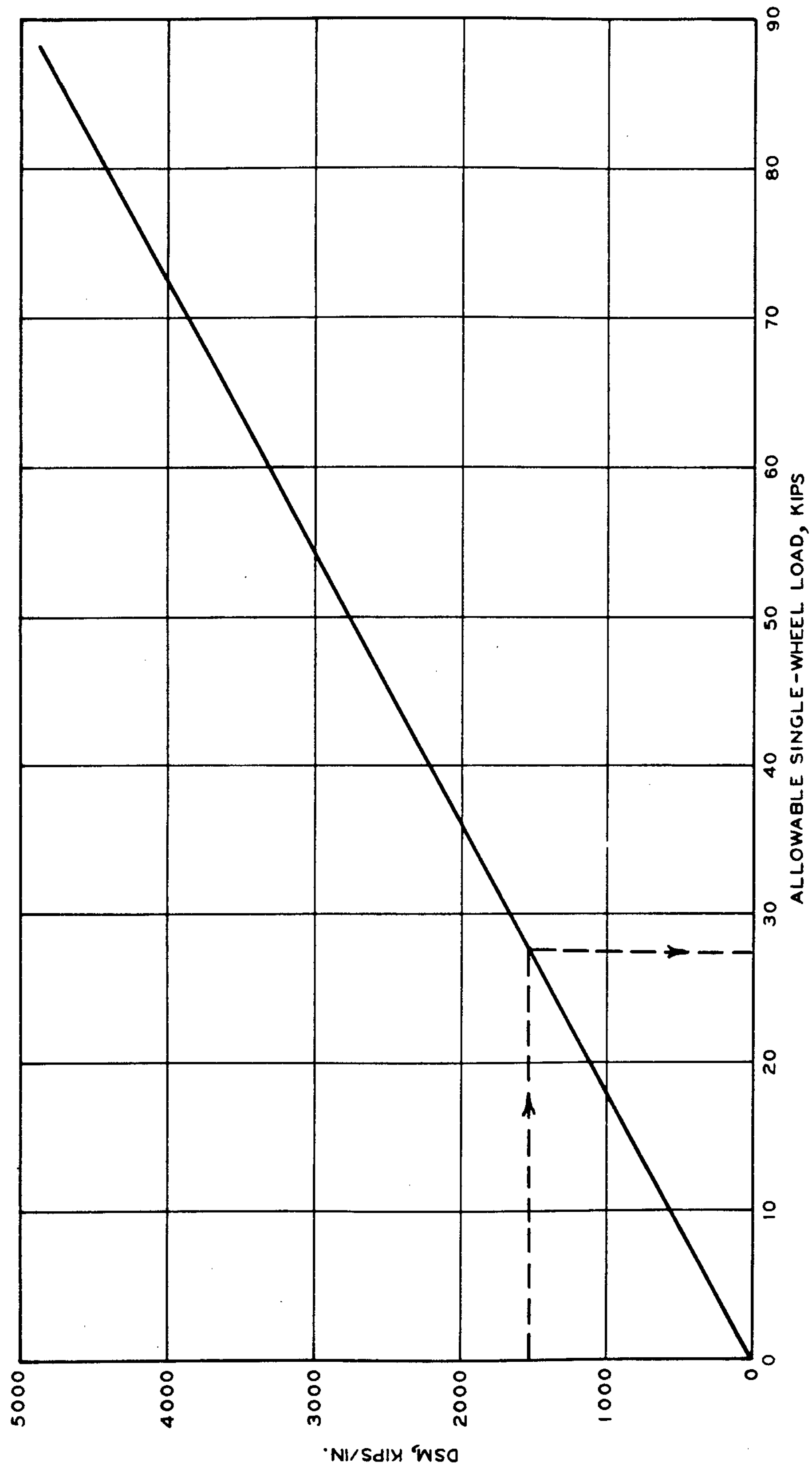

Figure 5. Evaluation curve for rigid pavement

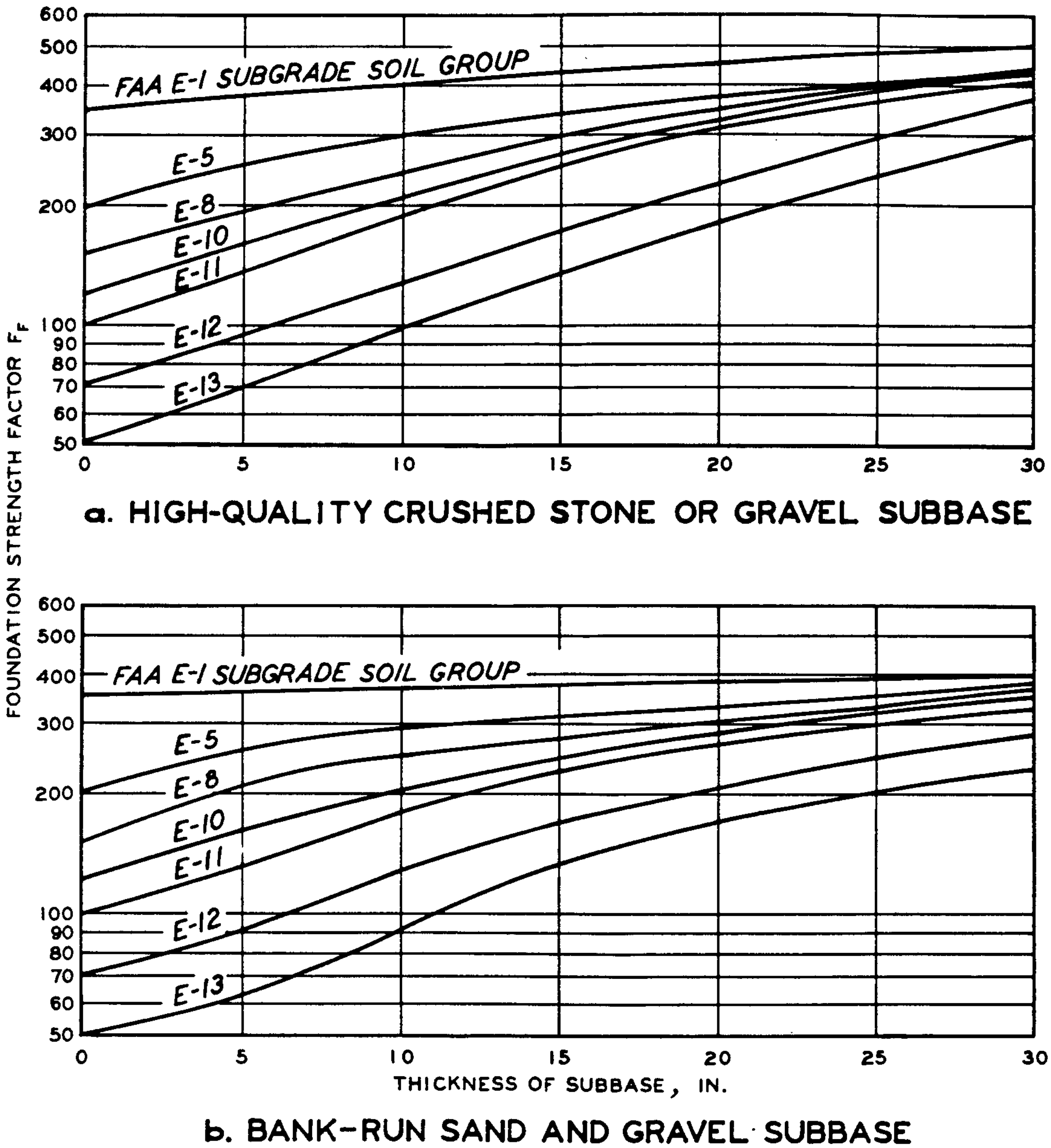

Figure 6. F_F versus subbase thickness

6.1.3 Step 3

Using ℓ , determine the load factor F_L from Figure 7, 8, 9, or 10, depending upon the gear configuration of the aircraft for which the evaluation is being made.

6.1.4 Step 4.

Multiply the allowable single-wheel load from Step 1 by the F_L value determined from Step 3 to obtain the gross aircraft loading.

6.1.5 Step 5.

Multiply the gross aircraft loading from Step 4 by the appropriate traffic factor from Table 1 to obtain the allowable aircraft gross loading for critical areas for the pavement being evaluated. For the case of high-speed turnoffs, the computed allowable gross load should be increased by multiplying by a factor of 1.18.

6.1.6 Step 6.

The allowable loading obtained from Step 5 assumes that the rigid pavement being evaluated is structurally sound and functionally safe. The computed allowable loading should be reduced if one or more of the following conditions exist at the time of the evaluation:

(1) The allowable load should be reduced by 10 percent if 25 percent or more of the slabs show evidence of pumping.

(2) The allowable load should be reduced by 25 percent if 30 to 50 percent of the slabs have structural cracking associated with load (as opposed to shrinkage cracking, uncontrolled contraction cracking, frost heave, swelling soil, etc.). If more than 50 percent of the slabs show load-induced cracking, the pavement should be considered failed.

(3) The allowable loading should be reduced by 25 percent if there is evidence of excessive joint distress such as continuous spalling along longitudinal joints, which would denote loss of the load-transfer mechanism.

6.2 <u>Flexible Pavement Evaluation</u>

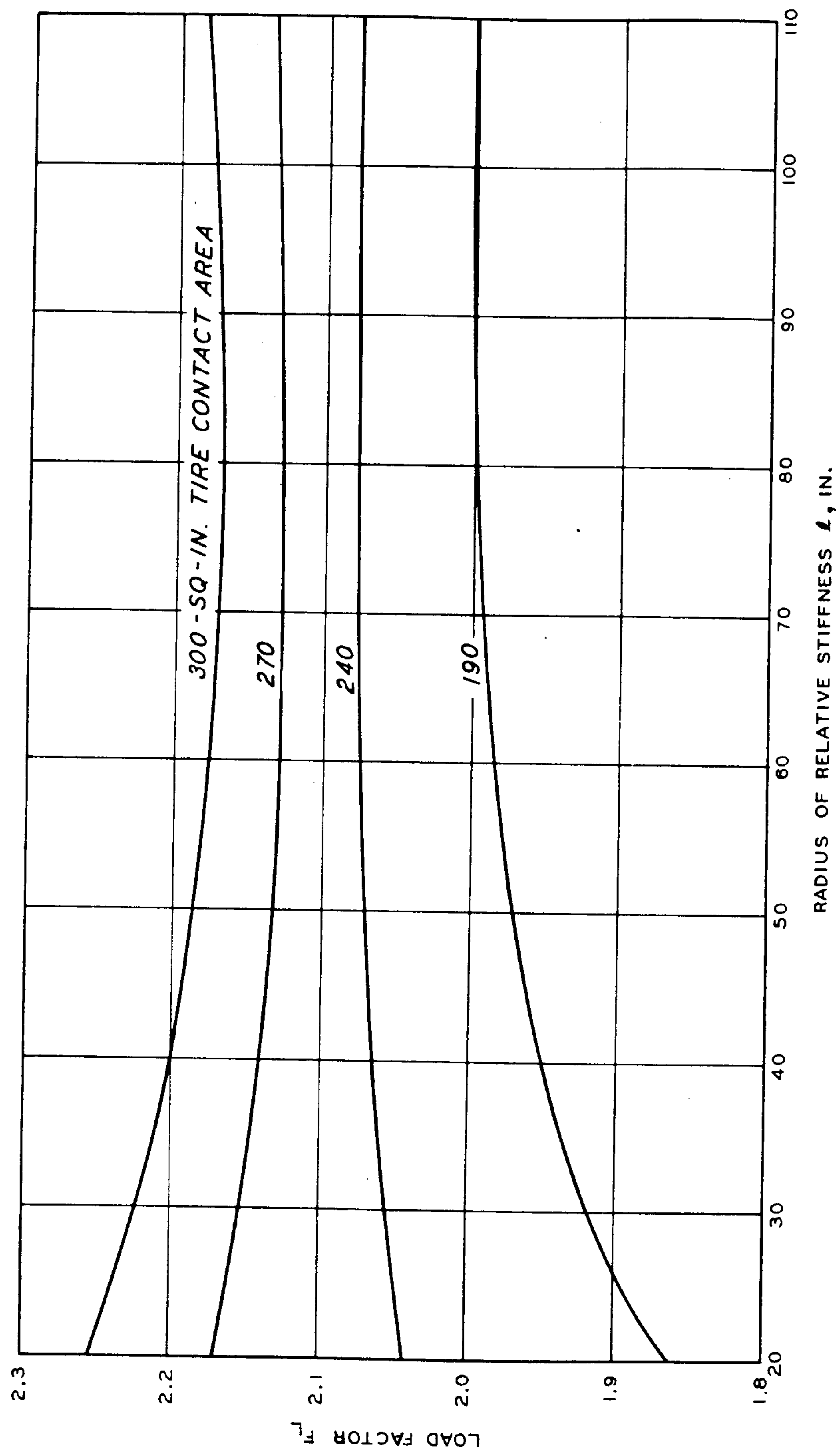

Figure 7. F_L versus ℓ for single-wheel aircraft on rigid pavement

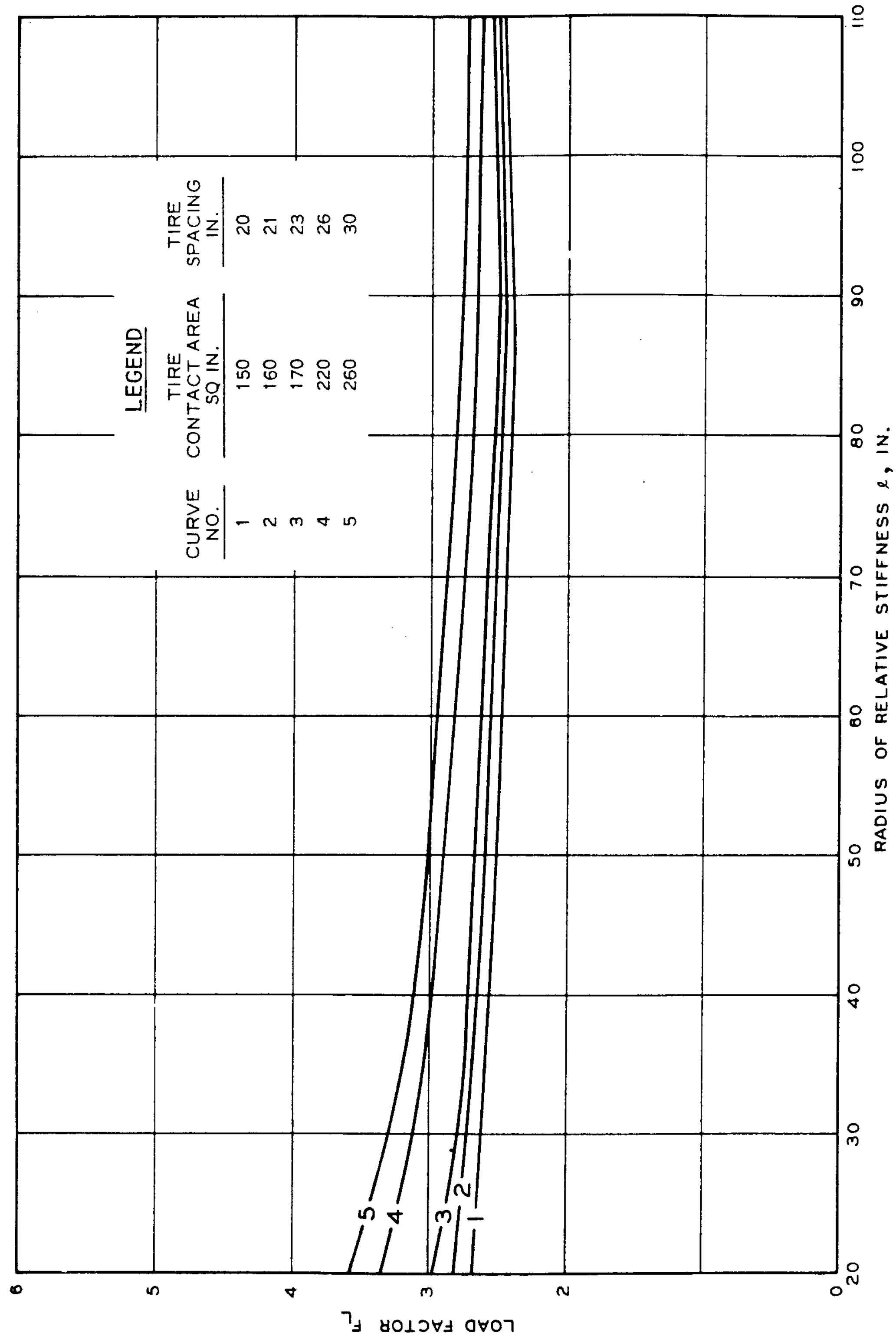

Figure 8. F_L versus ℓ for dual-wheel aircraft on rigid pavement

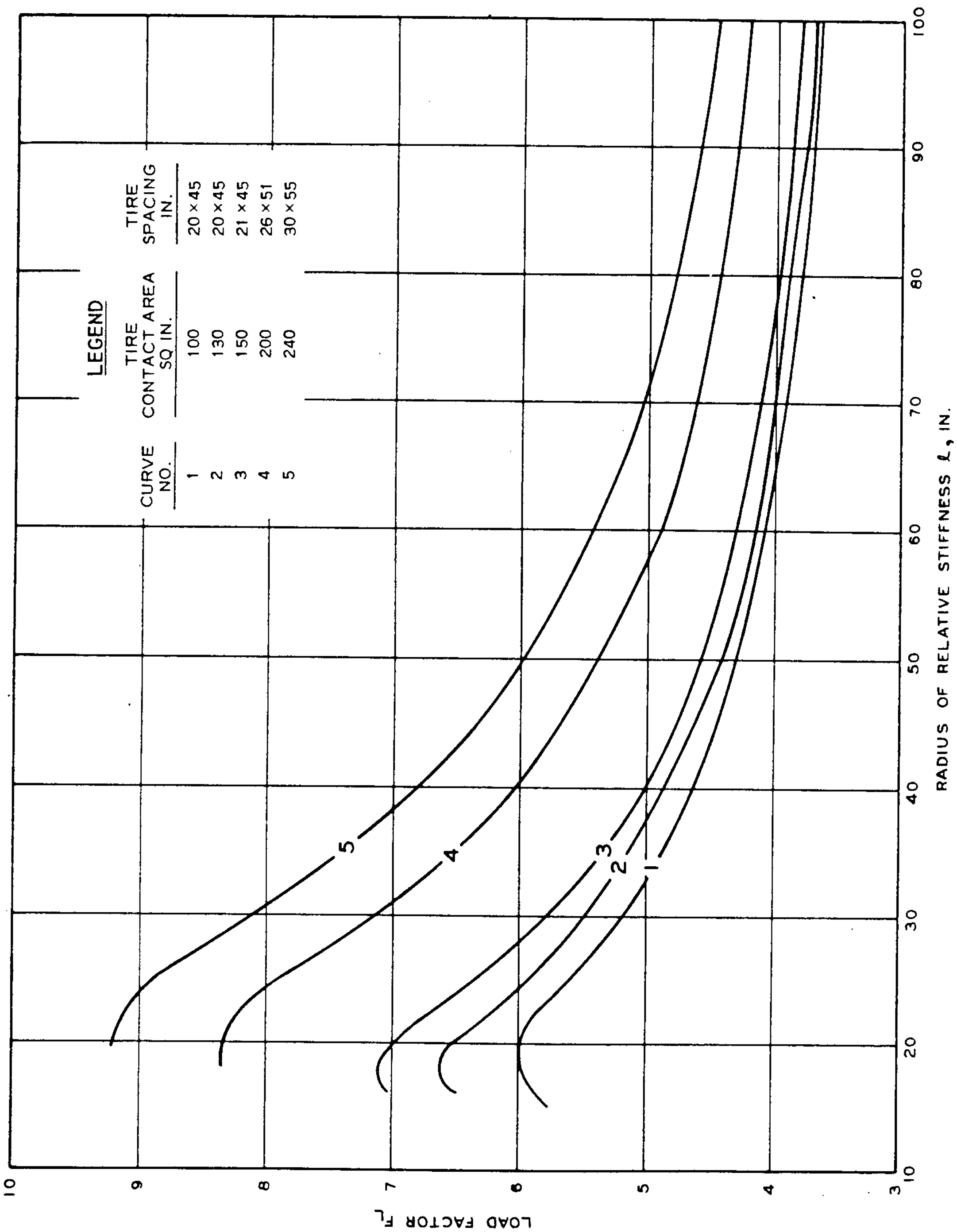

Figure 9. F_L versus ℓ for dual-tandem aircraft on rigid pavement

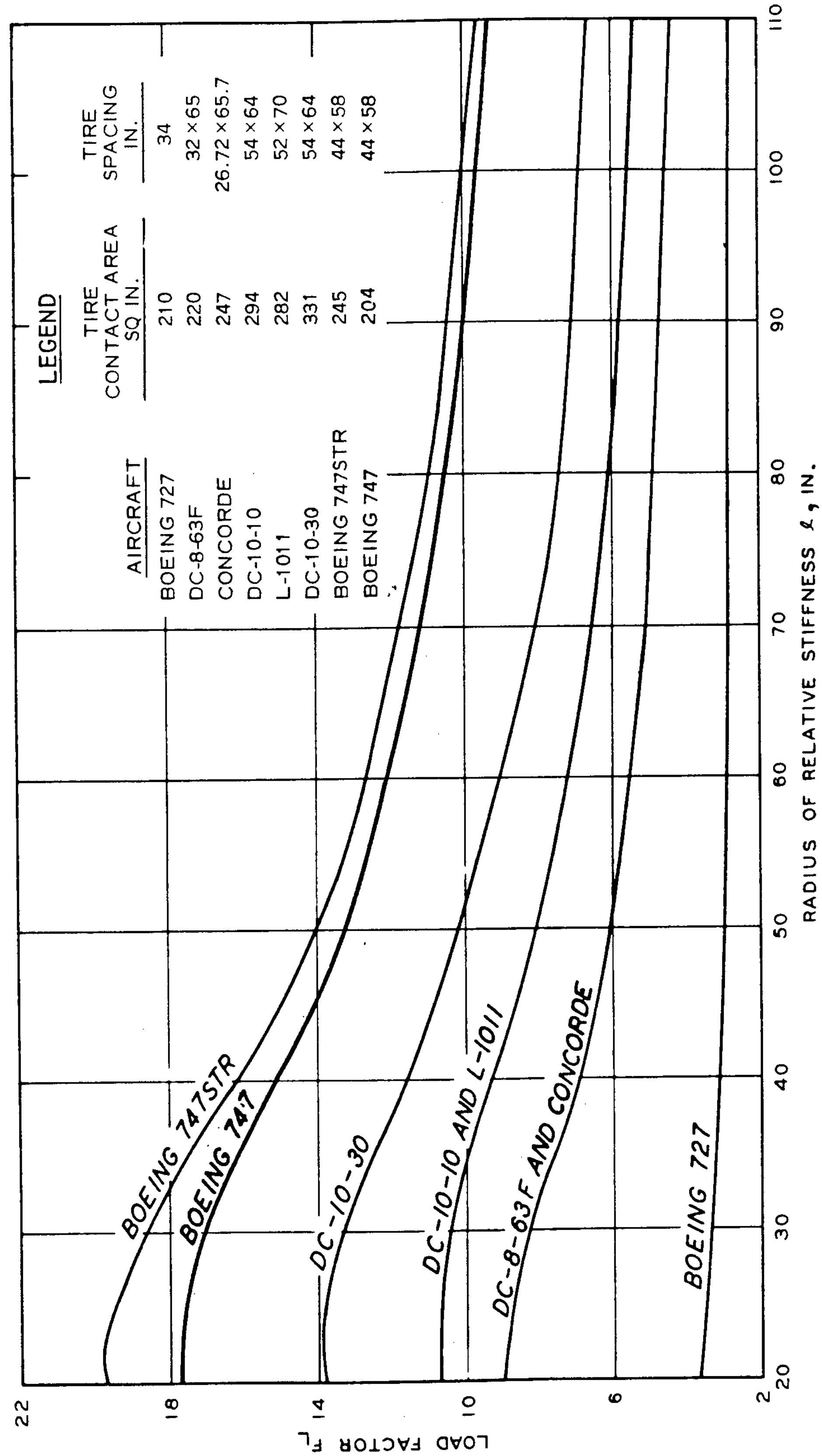

Figure 10. F_L versus ℓ for various jet aircraft on rigid pavement

Table 1

Traffic Factors for Flexible and Rigid Pavements

Aircraft	Traffic Factor for Cited Annual Departure Level for 20-Year Design Life									
	1,200		3,000		6,000		15,000		25,000	
	Flexible	Rigid	Flexible	Rigid	Flexible	Rigid	Flexible	Rigid	Flexible	Rigid
30-kip single-wheel	0.94	1.00	1.01	0.93	1.05	0.86	1.11	0.79	1.14	0.75
45-kip single-wheel	0.94	1.00	1.01	0.92	1.05	0.85	1.11	0.78	1.14	0.75
60-kip single-wheel	0.94	1.00	1.01	0.91	1.05	0.85	1.11	0.78	1.14	0.74
75-kip single-wheel	0.94	1.00	1.01	0.91	1.05	0.84	1.11	0.77	1.14	0.74
50-kip dual-wheel	0.84	0.97	0.87	0.88	0.89	0.82	0.91	0.75	0.92	0.72
75-kip dual-wheel	0.84	0.96	0.87	0.87	0.89	0.82	0.91	0.75	0.92	0.72
100-kip dual-wheel	0.84	0.96	0.87	0.87	0.89	0.81	0.91	0.75	0.92	0.72
150-kip dual-wheel	0.84	0.95	0.87	0.86	0.89	0.81	0.91	0.74	0.92	0.71
200-kip dual-wheel	0.84	0.95	0.87	0.86	0.89	0.81	0.91	0.74	0.92	0.71
100-kip dual-tandem	0.78	0.99	0.79	0.89	0.80	0.83	0.81	0.77	0.82	0.73
150-kip dual-tandem	0.78	0.98	0.79	0.88	0.80	0.82	0.81	0.76	0.82	0.73
200-kip dual-tandem	0.78	0.97	0.79	0.88	0.80	0.82	0.81	0.75	0.82	0.72
300-kip dual-tandem	0.78	0.95	0.79	0.87	0.80	0.81	0.81	0.75	0.82	0.72
400-kip dual-tandem	0.78	0.95	0.79	0.86	0.80	0.81	0.81	0.74	0.82	0.71
Boeing 727	0.84	0.95	0.87	0.87	0.89	0.81	0.91	0.75	0.92	0.71
DC-8-63F	0.78	0.95	0.79	0.87	0.80	0.81	0.81	0.74	0.82	0.71
Boeing 747	0.70	0.97	0.70	0.88	0.705	0.82	0.71	0.75	0.71	0.72
DC-10-10	0.78	0.96	0.79	0.88	0.80	0.82	0.81	0.75	0.82	0.72
DC-10-30	0.78	0.96	0.79	0.87	0.80	0.82	0.81	0.75	0.82	0.72
L-1011	0.78	0.96	0.79	0.88	0.80	0.82	0.81	0.75	0.82	0.72
Concorde	0.78	0.94	0.79	0.86	0.80	0.80	0.81	0.74	0.82	0.71

6.2.1 Step 1.

Using the DSM corrected for nonlinear effects and adjusted to the standard temperature, determine the pavement system strength index S_p from Figure 11.

6.2.2 Step 2.

Using the total thickness t of flexible pavement above the subgrade, compute the factor F_t for critical pavements as

$$F_t = 0.067t$$

or for high-speed taxiways as

$$F_t = 0.074t$$

6.2.3 Step 3.

Using F_t determined in Step 2, enter Figure 12 and determine the ratio of the subgrade strength factor SSF to the pavement system strength index S_p.

6.2.4 Step 4.

Compute the subgrade strength factor SSF by multiplying SSF/S_p by the value of S_p determined in Step 1.

6.2.5 Step 5.

Evaluate the pavement for any aircraft desired as follows:

(1) Select the aircraft or aircraft main gear configuration for which the evaluation is being made and determine the tire contact area A of one wheel of the main landing gear (see Table 2).

(2) Select the annual departure level for each aircraft for which the evaluation is being made and determine the traffic factor α for each aircraft from Table 1.

*

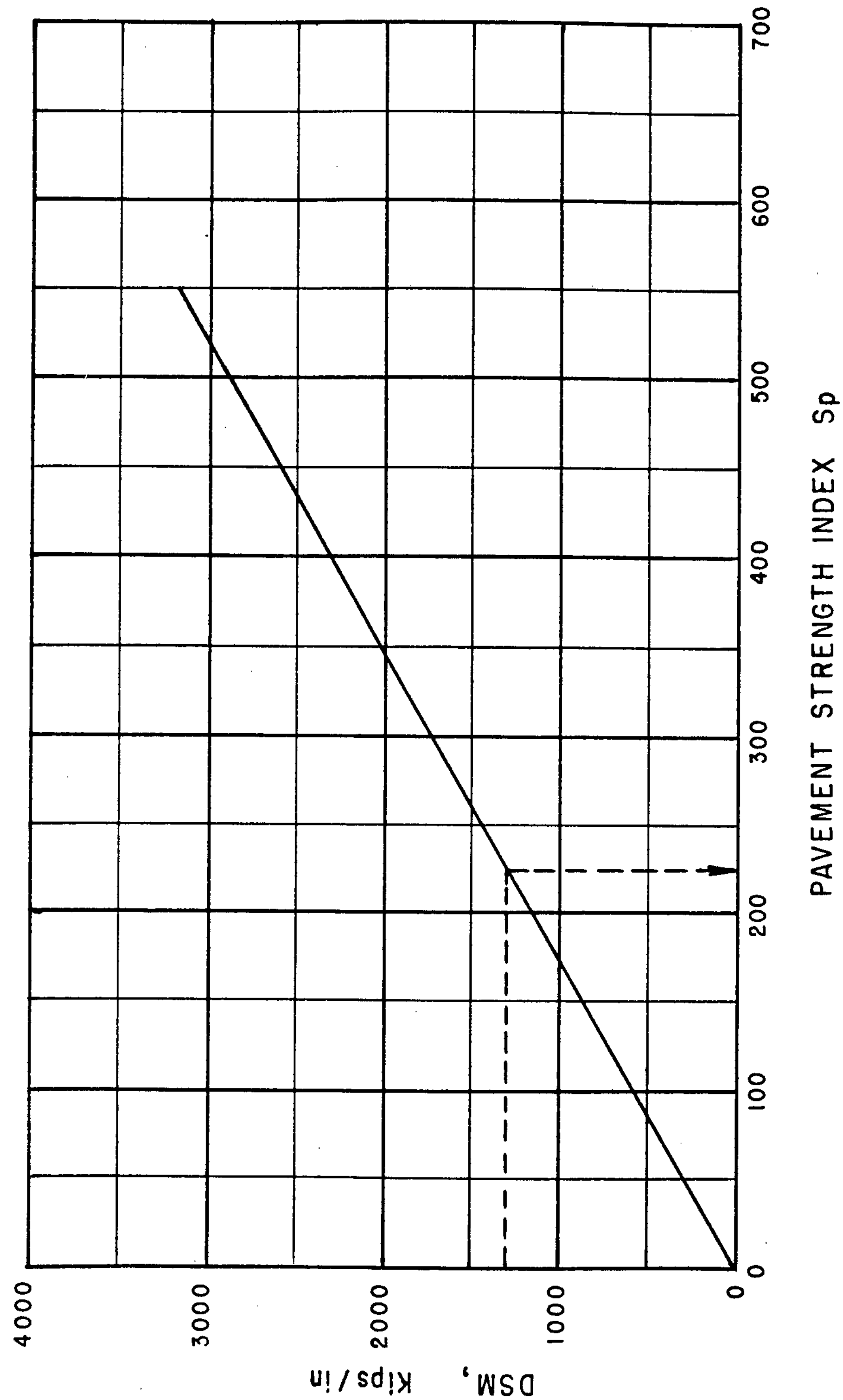

Figure 11. Evaluation curve for flexible pavement

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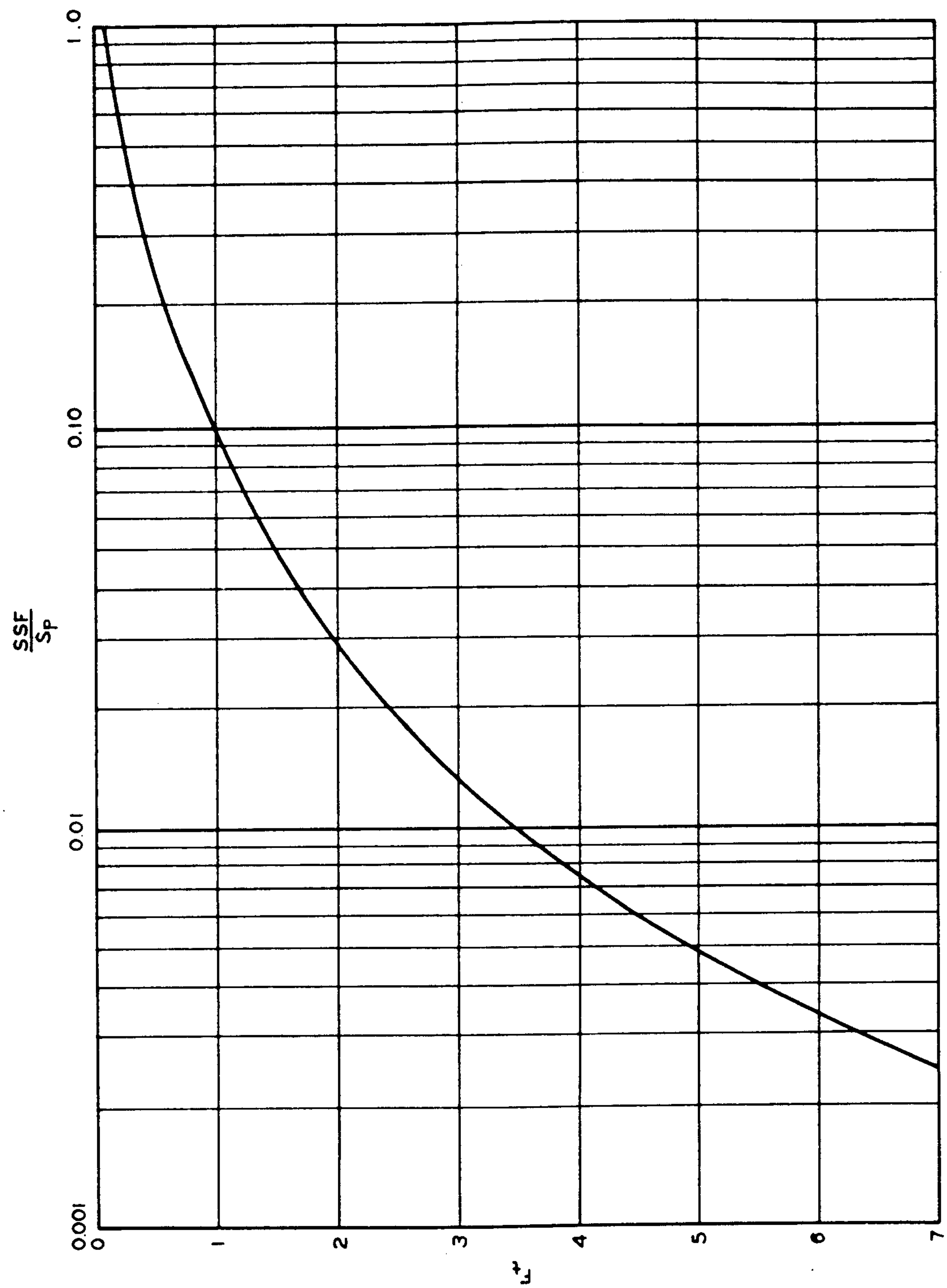

Figure 12. F_t versus $\frac{SSF}{S_p}$

Table 2

Aircraft Tire Contact Areas and
Total Number of Main Gear Wheels

Aircraft	Tire Contact Area sq in.	Total No. of Main Gear Wheels
30-kip single-wheel	190	2
45-kip single-wheel	240	2
60-kip single-wheel	270	2
75-kip single-wheel	300	2
50-kip dual-wheel	150	4
75-kip dual-wheel	160	4
100-kip dual-wheel	170	4
150-kip dual-wheel	220	4
200-kip dual-wheel	260	4
100-kip dual-tandem	100	8
150-kip dual-tandem	130	8
200-kip dual-tandem	150	8
300-kip dual-tandem	200	8
400-kip dual-tandem	240	8
Boeing 727	210	4
DC-8-63F	220	8
Boeing 747	204	16
Boeing 747 STR	245	16
DC-10-10	294	8
DC10-3	331	10
L-1011	282	8
Concorde	247	8

(3) Compute the factor F_t for each aircraft for which the evaluation is being made for critical pavements as

$$F_t = \frac{t}{\alpha\sqrt{A}}$$

or for high-speed taxiways as

$$F_t = \frac{t}{0.9\,\alpha\sqrt{A}}$$

(4) Enter Figure 12 with F_t and determine SSF/S_p.

(5) Compute the pavement system strength index S_p for the aircraft being evaluated by dividing SSF determined in Step 4 by the ratio SSF/S_p determined in Substep (4) above.

(6) Multiply S_p by the tire contact area A from Table 2 to obtain the equivalent single-wheel load (ESWL) of each aircraft for which the evaluation is being made.

(7) Enter Figure 13, 14, or 15 with the total pavement thickness t and determine the percent ESWL for the controlling number of wheels of the aircraft for which the evaluation is being made, i.e., if the aircraft has a dual-wheel assembly with a dual spacing of 26 in., use Curve 4 in Figure 13, or, if the evaluation is for the Boeing 747STR aircraft, use the Boeing 747STR curve in Figure 15.

(8) The allowable gross aircraft load for the pavement being evaluated and for the traffic volume selected is then obtained from

$$\text{Allowable gross aircraft load} = \frac{\text{ESWL}}{\%\ \text{ESWL}} \times \frac{1}{W_c} \times \frac{W_M}{0.95}$$

where

ESWL = determined by Substep (6)

% ESWL = determined by Substep (7)

W_c = number of controlling wheels used to determine the % ESWL from Figure 13, 14, or 15

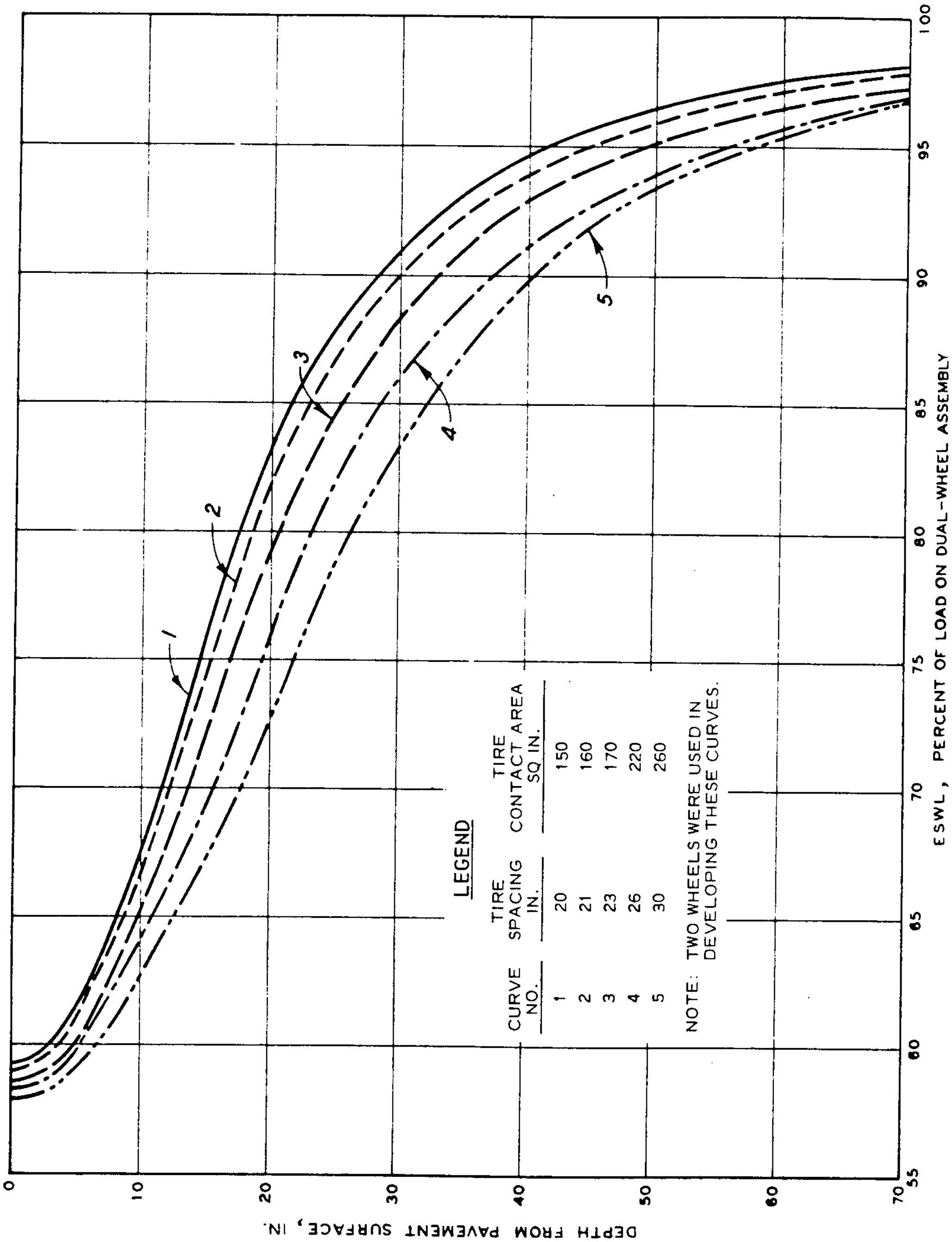

Figure 13. ESWL curves for dual-wheel aircraft on flexible pavement

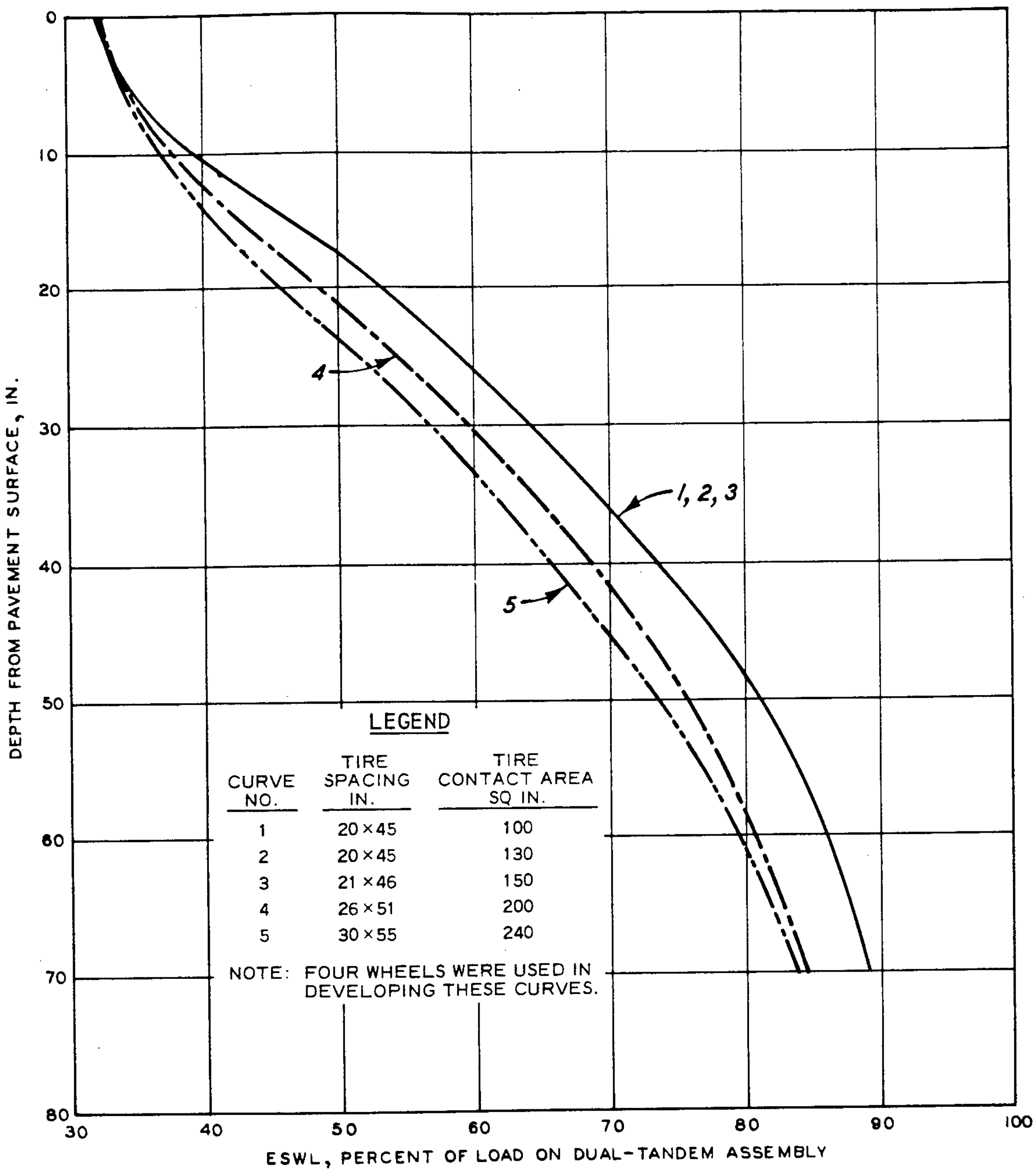

Figure 14. ESWL curves for dual-tandem aircraft on flexible pavement

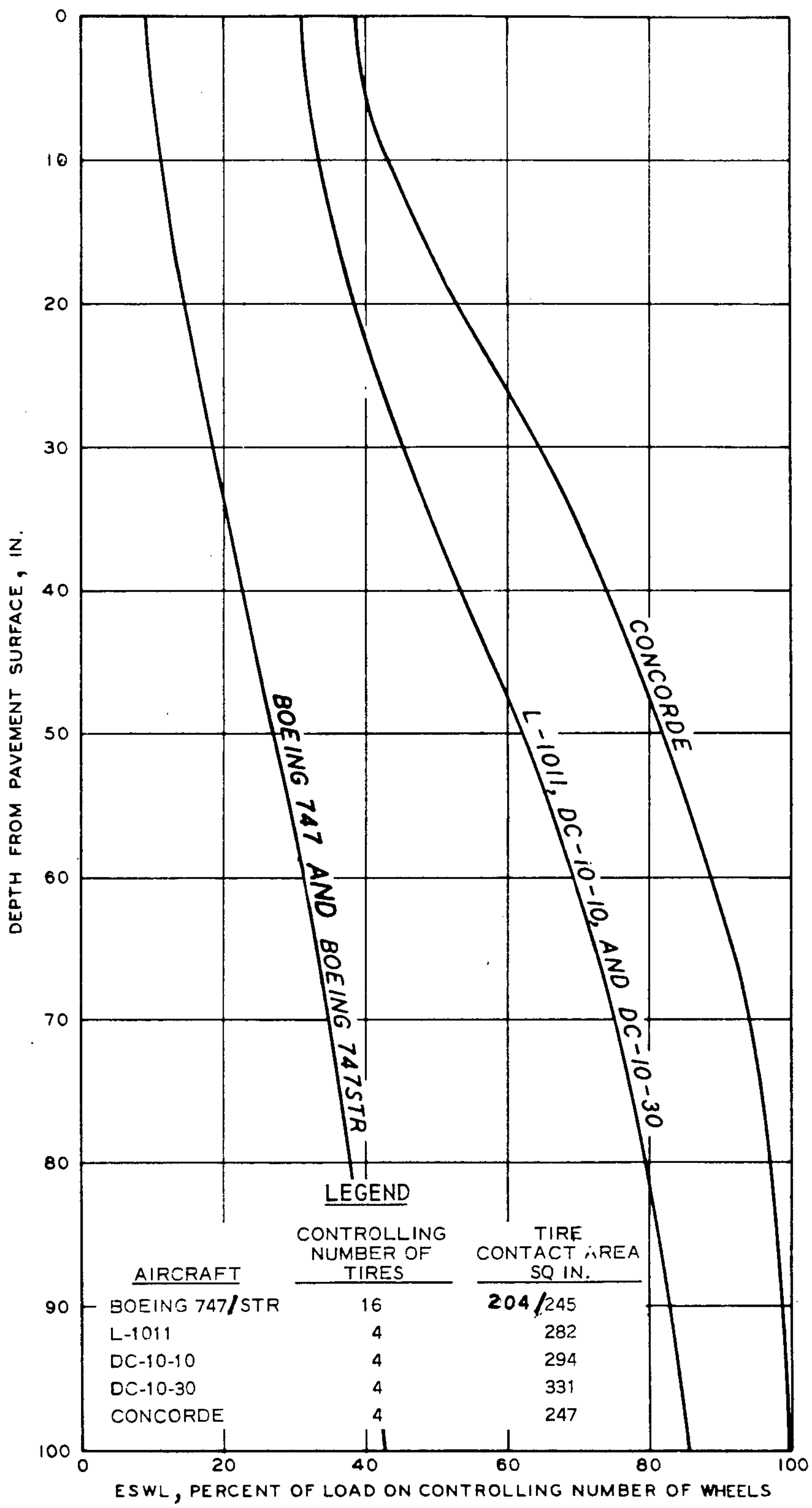

Figure 15. ESWL curves for various jet aircraft on flexible pavement

W_M = total number of wheels on all main gears of the aircraft (see Table 2) for which the evaluation is being made (does not include wheels on nose gear)

7 SUMMARIZATION

The evaluation procedure presented herein is what must be referred to as a first generation procedure. That is, further work is underway to extend the applicability of this procedure, and it will be updated as appropriate. In addition, research is underway which will establish the NDT evaluation procedure on a more theoretical basis and thus further enhance its applicability. The allowable loadings determined using the procedure presented herein are within acceptable limits of accuracy as compared with those determined using other recognized evaluation procedures. This procedure has the added advantages of being less costly, presenting less interference to normal airport operations, and providing the evaluating engineer with much more data on which to base his decisions. Also, in addition to their utility for arriving at allowable aircraft loading, the DSM values are useful for qualitative comparisons between one pavement area and another (DSM values on flexible pavements should not be compared with those on rigid pavements) and for locating areas which may show early distress and which may warrant further investigation. As more experience is gained with the DNT techniques and interpretation of data, it is envisioned that many other uses of the concept will emerge.

APPENDIX 2. RELATED READING MATERIAL

1. The latest issuance of the following free publications may be obtained from the Department of Transportation, Subsequent Distribution Unit, M-494.3, Washington, D.C. 20590. Advisory Circular 00-2, lists circulars and changes thereto.

   a. AC 00-2, Federal Register, Advisory Circular Checklist and Status of Regulations.

   b. AC 150/5000-3, Address List for Regional Airports Divisions and Airports Districts Offices.

   c. AC 150/5320-6, Airport Pavement Design and Evaluation.

2. The following reports are available to the public through the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161

   a. Nondestructive Vibratory Testing of Airport Pavements; Volume I: Experimental Test Results and Development of Evaluation Methodology and Procedure, by James L. Green and Jim W. Hall, FAA-RD-73-205-I, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi 39180.

   b. Nondestructive Vibratory Testing of Airport Pavements; Volume II: Theoretical Study of the Dynamic Stiffness and Its Application to the Vibratory Nondestructive Method of Testing Pavements, by Richard Weiss, FAA-RD-73-205-II, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 39180.